Keck Adaptive Optics Note 716

**DRAFT**

Next Generation Adaptive Optics

Preliminary Design

Wavefront Error Budgets

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# Abstract

The purpose of this note is to summarize the wavefront error and encircled energy budgets for the Next-Generation Adaptive Optics (NGAO) system at the time of the NGAO Preliminary Design Review.

These budgets are based upon a set of architecture design choices and functional requirements flowdowns consistent with the NGAO System Requirements, which are maintained in an online Requirements Management database product, Contour, developed by JAMA Software, Inc. and commercially licensed by W.M. Keck Observatory.

# Revision Sheet

|  |  |  |
| --- | --- | --- |
| **Release No.** | **Date** | **Revision Description** |
| Rev. 0.1 | 4/5/10 | Initial draft by R. Dekany |
| Rev 0.2 | 4/6/10 | Added Gal Assembly Ensquared Energy curves, NGS WFS TWFS mode TT error vs. guide star mag, histogram comps to Keck 2 AO, and more text to prior sections. |
|  |  |  |
|  |  |  |

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#  Introduction

##  Acronyms and Definitions

DAVINCI A new science instrument under development as part of NGAO

d-IFU Deployable IFU

EncE Encircled Energy

EnsqE Ensquared Energy

FoV Field of View (the field observed by a single detector array)

FoR Field of Regard (the technical or patrol range of a sensor)

FWHM Full-Width at Half-Maximum = 2.355  for a Gaussian distribution

HOWFS High-order wavefront sensor

IFU or IFS Integral Field (Unit) Spectrograph

LGS Laser Guide Star

LO WFS Low-Order Wavefront Sensor

mas Milliarcseconds

NGAO Next-Generation Adaptive Optics

NGS Natural Guide Star

NGWFC Next-Generation Wavefront Controller

PSF Point Spread Function

RMS Root Mean-Squared

TT Tip-tilt

TWFS Truth Wavefront Sensor

WCS Well-corrected subaperture.

WFE Wavefront reconstruction error

” arcseconds

’ arcminutes

## Purpose

The purpose of this document is to document the assumptions, architecture choices, performance flowdown requirements, and expected wavefront error and encircled energy performance for the NGAO science cases.

## Scope

This document includes all defined NGAO science case error budgets, sample TT sharpening budgets, and several trade studies performed to capture NGAO performance.

## Related Documents

### Configuration-Controlled Documents

* KAON 550, NGAO System Configurations
* KAON 636, Observing Operations Concept Document
* KAON 721, Wavefront Error Budget Tool
* KAON 722, NGAO High-Contrast Error Budget Tool
* KAON 723, Performance Flowdown Budgets

### Previous NGAO Performance Documents

* KAON 452, MOAO versus MCAO Trade Study Report
* KAON 465, NGAO LGS Wavefront Sensor: Type and Number of Subapertures Trade Study
* KAON 470, NGAO Sky Coverage Modeling
* KAON 471, NGAO Wavefront Error and Ensquared Energy Budgets (for System Design Phase)
* KAON 475, Tomography Codes Comparison and Validation for NGAO
* KAON 480, Astrometry for NGAO
* KAON 492, NGAO Null-Mode and Qadratic Mode Tomography Error
* KAON 497, NGAO High-Contrast and Companion Sensitivity Performance Budget
* KAON 503, Mauna Kea Ridge Turbulence Models
* KAON 504, NGAO Performance vs. Technical Field of View for LOWFS Guide Stars
* KAON 594, Plan to Address Phased Implementation and Descope Options
* KAON 601, NGAO Point and Shoot (SPIE 2008)
* KAON 621, Noise Propagator for Laser Tomography AO
* KAON 629, Error Budget Comparison with NFIRAOS
* KAON 635, Point & Shoot Study
* KAON 644, Build-to-Cost Architecture Performance Analysis
* KAON 710, Latency, Bandwidth, and Cotrol Loop Residual Relationships

### Keck AO Performance Analyses

* KAON 461, Wavefront Error Budget Predictions & Measured Performance for Current & Upgraded Keck AO
* KAON 462, NGAO Trade Study: Keck AO Upgrade
* KAON 469, Effect of Keck Segment Figure Errors on Keck AO Performance
* KAON 482, Keck Telescope Wavefront Error Trade Study
* KAON 500, Keck AO Upgrade Feasibility

### References

* CIN 626, PALM-3000 Error Budget Summary
* J. W. Hardy, *Adaptive Optics for Astronomical Telescopes* (Oxford U. Press, 1998).
* KAON 416, Atmospheric Sodium Density form Keck LGS Photometry
* KAON 477, Modeling Low Order Aberrations in Laser Guide Star AO Systems (OE 2007)
* KAON 478, Modeling Laser Guide Star Aberrations (OSA 2007)
* KAON 574, Systems Engineering Management Plan
* KAON 583, Work Breakdown Structure Definitions

# NGAO Performance Requirements

The highest-level performance requirements for NGAO are documented in the Systems Requirements section of the NGAO Requirements Contour Database (see Appendix A), with the key requirement for wavefront and ensquared energy documented in SR-20, summarized in Table 1.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **NGAO Key Science Case** | **High-order RMS Wavefront Error (nm)** | **RMS TT Error (mas)** | **Effective Total RMS Wavefront Error (nm)** | **Ensquared Energy within a 70 mas spaxel** | **Observing Passband** | **Typical Single-Integration Time (sec)** |
| Galaxy Assembly | 163 | 4.9 | 185 | 74 | K | 1800 |
| Nearby AGN's | 163 | 4.7 | 181 | 26 w/in 34 mas | Z | 900 |
| Galactic Center | 190 | 2.2 | 193 | 59 | H | 10 |
| Exoplanets | 162 | 3.8 | 174 | 68 | H | 300 |
| Minor Planets | 164 | 4.7 | 181 | 25 | K | 120 |
| Io | 115 | 2.1 | 117 | 83 | K | 10 |

Table . High-level NGAO Performance Requirements Summary from SR-20.

During the NGAO design phases, there has been a close iterative process of feedback between the technical and science teams to determine the best science return obtainable, particularly in light of the Build-to-Cost project decision documented in KAON 642. For reference the historical transition of the performance requirements, including current Keck AO Performance as documented in KAON 461, is shown in Table 2. In general, cost reductions have resulted in the performance degradation of some science cases (typically reflecting the loss of the wide-field d-IFU capability) and the performance enhancement of others.

# Architectural and Observational Elements

The NGAO WFE budgets are developed using a common WFE budget Microsoft Excel spreadsheet tool developed at Caltech by R. Dekany and collaborators over the past 10 years. It has been extensively validated against other budgets (Wizinowich, Neyman, van Dam, others), detailed Monte Carlo simulations (Arroyo, LAOS), and across projects (see KAON 629 for one example). Fundamentally, it allows selection of an adaptive optics system configuration (such as Keck 2 AO, Keck 1 AO, or NGAO), a Science Case (such as Galaxy Assembly, Io, T Tauri objects, etc.), and a science instrument (such as DAVINCI, OSIRIS, PHARO, etc.) The architectural and observational differences between these choices are almost entirely captured on a single ‘Input Parameters’ worksheet of the workbook. The selection of WFS camera frame rates and offaxis NGS brightnesses and distances are typically optimized parameters that are found subject to constraints of necessary sky coverage fraction or guide star brightness, in the case of a known specific science target. Thus, each error budget for NGAO corresponding to each key science case, assumes operation at a slightly different frame rate[[1]](#footnote-1).

Error budgets are summarized on the ‘Optim’ worksheet, as this is location of the optimization parameters. (Optim is commonly used for the generation of trade study results, as well.) Separate error budgets are maintained for the science path, the sharpening of field TT stars, and for the wavefront error residual sensed by the TWFS (if applicable). For patrolling LGS TT sharpening systems, the camera frame rates of corresponding HO LGS WFS’s are separately optimized. Additional description of this tool is provided in Appendix C.

|  |  |  |  |
| --- | --- | --- | --- |
| **NGAO Key Science Case** | **2006 Keck 2 AO Performance in 75th Percentile Best Seeing****(approx.)** | **Expected Keck 1 AO Performance in Median Seeing(approx.)** | **NGAO Requirementsin Median Seeing** |
| **Proposal[[2]](#footnote-2),[[3]](#footnote-3)** | **SDR** | **B2C** | **Current(PDR)** |
| Galaxy Assembly | 557[[4]](#footnote-4) | 529[[5]](#footnote-5) | 197[[6]](#footnote-6) | 257 | 204 | 185 |
| Nearby AGN's | 557 | 529 | 197 | N/A | 182 | 181[[7]](#footnote-7) |
| Galactic Center | N/A | 387[[8]](#footnote-8) | 182 | 184 | 189 | 193 |
| Exoplanets | 378[[9]](#footnote-9) | 311[[10]](#footnote-10) | N/A | 155 | 171 | 174 |
| Minor Planets | 557 | 529 | 131 | 175 | 177 | 181[[11]](#footnote-11) |
| Io | 258[[12]](#footnote-12) | 210[[13]](#footnote-13) | 125 | 148 | N/A | 117 |

Table . Progression of AO Performance Requirements to Date (N/A = Not available).

The NGAO system architecture choices are documented in the configuration region of the Input Summary tab of the Wavefront Error Budget Tool, KAON 721. The key elements of this table are summarized in Table 5. Not shown here, but a critical to budget fidelity is an area of the Input Summary that selects optical pass-bands for each WFS camera. (Also not shown are optical transmission models that track expected photon transmission through each AO system configuration.)

# Science Case Parameters

Science Case parameters for NGAO have been updated by Max and McGrath during the NGAO preliminary design phase. The updated parameters are shown for convenience in Table 3.



Table . Science Cases Parameters for NGAO PD phase.

The performance summary of the NGAO PD phase design for all these Science Cases is summarized in Table 4.

XXX Need to compile the full performance matrix for all the science cases in Table 3. XXX

Table . Summary of NGAO Science Case Performance.



Table . Architectural decisions and key parameters for NGAO for the Galaxy Assembly Science Case.

# Detailed Error Budget for Galaxy Assembly Key Science Case

## Science Path Wavefront Error Budget



Table . Galaxy Assembly Case Wavefront and Ensquared Energy Budget

## TT Sharpening Budget



Table . Galaxy Assembly TT Sharpening Budget

## TWFS Budget



Table . Galaxy Assembly TWFS Budget

#  LGS Mode operation with 5 x 5 subaperture NGS WFS TWFS mode

## Describe the mode of operation

There are two NGAO modes of operation that require use of the visible-light NGS WFS in a 5x5 subaperture pupil sampling mode: Pupil Fixed mode operation (typical of exoplanet searches and characterization) and in Image Fixed mode when the availability of field NGS for LO WFS sensing of TT and blind mode sensing is not favorable compared to use of the science target itself for both TT and blind mode information.

## Performance Estimate

In theory, it may be possible to combine information from the NGS WFS in TWFS mode with information from the LO WFS, to further optimize performance, but this will not be investigated here. Instead, we would like to understand the TT performance (only) of the NGS WFS in TWFS mode, as a function of science target brightness, and more specifically we’re interested in knowing how the red-wavelength NGS WFS cutoff choice affects performance in the NGS WFS TWFS mode. The results of just such a trade study are shown in Figure 4.



Figure . Performance of the NGAO NGS WFS for TT measurement, when operating in 5x5 subaperture TWFS mode, for NGS passband approximately 500 – 900 nm, compared to passband approximately 500 – 700 nm. These curves are optimized for best TT performance, and do not include the degradation of TWFS sensing of the laser tomography blind modes as the NGS WFS frame rate is slowed. The indicated optimal NGS WFS frame rate corresponds to the 500 – 900 nm passband case.

In generating Figure 1, we assume that the NGS WFS frame rate is optimized to provide the best TT measurement, without regard to the potential impact on its ability to accurately measure the laser tomography blind modes. If we assume that the need for accurate blind mode measurement requires us to operate the NGS WFS in TWFS mode no slower than 200 Hz (an admittedly arbitrary number), the quality of NGS WFS TT sensing breaks down considerable faster, as shown in Figure 2.



Figure Performance of the NGAO NGS WFS for TT measurement, when operating in 5x5 subaperture TWFS mode, for NGS passband approximately 500 – 700 nm, with a minimum frame rate limit of 200 Hz. This may be more indicative of TT operation when the NGS WFS is required to read out relatively fast to maintain good blind mode measurement.

# Trade Studies

## Performance vs. Seeing

NGAO will have to operate in a wide range of natural seeing conditions, so it is interesting to understand the sensitivity of performance to changes in the Fried parameter, r0. This is shown for the Galaxy Assembly Science Case in Figure 3.



Figure . K-band performance for the Galaxy Assembly Science Case as a function of r0 at 0.5 microns.

## Performance vs. Wind Speed

The 3-dimensional wind profile of the atmosphere above Mauna Kea can vary dramatically. Although we adopt as our median a value of 9.5 m/s, we would like to understand how performance degrades with increasing turbulence-weighted wind speed, and how it might improve under calmer conditions. Figure 4 demonstrates the sensitivity of performance, which is rather benign for the Galaxy Assembly Science Case, even for wind speeds treble our median assumption. As the wind speed is increased, the corresponding HO WFS frame rate increases (and recall, in the current KAON 721 model, this also simultaneously increases the HO WFS CCD pixel readout rate.) For a fixed pixel read rate, NGAO will have somewhat more performance sensitivity to high wind speeds, as the rejection bandwidth of atmospheric turbulence may not be able to keep up so optimally with increasing frame rate.



Figure . K-band performance for the Galaxy Assembly Science Case as a function of turbulence-weighted wind speed. The open marker indicates the median 9.5 m/s wind speed condition.

## Performance vs. Laser Return

Experience with the first-generation sodium D2-line resonant excitation LGS at Lick, Keck, and Palomar Observatories has shown that measured sodium photoflux can vary widely due to be sodium abundance fluctuations (see §7.4), but also because of variability in laser power and degradations in optical transmission in beam transfer uplink or AO system downlink optical systems.

We are interested in understanding the sensitivity of NGAO to variations in the expected sodium return photoflux. The results of two trade studies are shown in Figure 5 and Figure 6. In the first of these, we consider the impact of different levels of laser (spigot) power in absolute terms (assuming our usual “SOR-like” laser return) while in the second, we describe it as a percentage of the expected laser return (typically 55 photodetection events (PDE) / exposure time / subaperture, or 57 / (.1825^2) / 0.0011 = 1.55 x 106 PDE/sec/m2 or ~155 PDE/sec/cm2, for each of the 12.5W (spigot) fixed asterism LGS[[14]](#footnote-14)).



Figure K-band performance for the Galaxy Assembly Science Case as a function of fixed asterism laser power, holding patrolling asterism laser power constant at 25W (e.g. 3 x 8.33 W each.) The open marker indicates the baseline 50W of fixed asterism laser power (spigot).



Figure . K-band performance for the Galaxy Assembly Science Case as a function of fixed asterism laser return, relative to the expected return using our baseline conditions model (e.g. 3 x 109 atoms/cm2 sodium density, SOR-laser-like return, delivered and return transmission assumptions, etc.), holding patrolling asterism laser power constant at 25W (e.g 3 x 8.33 W each.) The robustness of NGAO to less-than-expected laser return is clear for this science case.

## Seeing, Wind Speed, and Sodium Abundance Monte Carlo Results

Although practically useful in understanding the sensitivities of NGAO performance to both seeing and turbulence-weighted wind speed variations, in practice NGAO will see on any given night seeing and wind speed values that are random variables drawn from some statistical distributions. In fact, there exists considerable detail on the statistics of these parameters at Mauna Kea. For my current purpose, however, an approximate form of these distributions will suffice to indicate the typical distribution of performance we might expect from a large number of observing nights. To quickly model this, I can assume that both r0 and wind speed are drawn from Gaussian probability distributions. Following the technique in ‘Numerical Recipes in C, 2nd Ed’, page 289, we generated in Excel draws of the form:

|  |  |  |
| --- | --- | --- |
|  | **Mean** | **Standard Deviation, ** |
| r0 at 0.5 microns | 0.16 m | 0.025 m |
| Wind speed | 9.5 m/s | 4 m/s |

where the distribution standard deviations, , are coarse estimates based on KAON 303. (A detailed determination of  Is unlikely to improve these results, as I contend we are within the uncertainty level of the model[[15]](#footnote-15).)

The results of 252 random draws (and frame rate optimizations) from this joint probably distribution is shown in Figure 7, for the case of mesospheric sodium abundance held constant at the below-median level of 3 x 109 atoms/cm2. Note, unlike the current Keck 2 AO system, NGAO is seen to vary rarely deliver performance less than about 60% K-band Strehl ratio. Moreover, the system is expected to deliver K-Strehls within a few percent of 78%, across varying different atmospheric conditions, a rather remarkable qualitative difference over current AO that we expect to improve both photometric accuracy and astrometric precision.



Figure . Predicted performance distribution for NGAO based upon 252 r0 and wind speed draws, holding sodium abundance constant at 3e9 atoms/cm2,, for the Galaxy Assembly Science Case.

Because sodium abundance can also vary, we repeated this random draw experiment, adding it as a third joint random variable:

|  |  |  |
| --- | --- | --- |
|  | **Mean** | **Standard Deviation, ** |
| Sodium abundance | 3.6 x 109 atoms/cm2 | 1.0 x 109 atoms/cm2 |

Where the mean is take from KAON 416 and the standard deviation estimated from the fact that experience has shown the large majority ( ~90%) of time density is thought to be between 1.6 x 109 and 5.6 x 109 atoms/cm2 (e.g. +- 2). This result, for 394 random draws, is shown in Figure 8. Not surprisingly, this histogram is shifted to somewhat higher performance compared to our earlier sub-median sodium abundance curve. Because sometimes the abundance can fall, even in conjunction with good seeing and slow winds, the (relatively) poorer performance tail is now seen to be extended, though still almost always above 60% K-Strehl.



Figure . Predicted performance distribution for NGAO based upon 394 r0, wind speed, and sodium abundance draws for the Galaxy Assembly Science Case.

To better appreciate the advantage of NGAO over current Keck 2 AO, we repeated the experiment described in Figure 8 with a mirror experiment, using the same parameter distributions, for our model of the Keck 2 AO system (previously validated as described in KAON 461). This result is shown in Figure 9. The first obvious benefit of NGAO is an approximately 3x improvement in K-band Strehl ratio over current Keck 2 AO, which direct improves telescope sensitivity for background-limited imaging. The difference in results distribution width is also quite striking, particularly if one considers the *relative* stability of the predicted results, with NGAO showing perhaps +- 4% variation around a 78% peak (+- 5% relative), while the Keck 2 AO result shows +- 10% around a 30% median, which is more like +- 33% relative variation.

The skewness of these distributions is also worth noting. For Keck 2 AO, the longer tail is toward good performance, so it is more likely that an observer will have heard of someone at some time having a particularly good result with Keck 2 AO, but the median performance, they’re average experience with AO, tends to fall short of this. For NGAO, on the other hand, we expect the user experience to be more often consistent with the maximum capability of the system. The occasional unfortunate night for an NGAO observer will doubtless draw heartfelt condolences from their colleagues.

More practically, NGAO instrument development will also benefit from this tendency to deliver more predictable image quality, perhaps by reducing the number of configurations, such as plate scales, that is typically necessary when delivered performance is widely variable.

Figure Predicted performance distribution for the current Keck 2 AO system based upon 150 r0, wind speed, and sodium abundance draws for the Galaxy Assembly Science Case. Note the change in Strehl Bin scale compared to the NGAO predictions.

## Performance vs. Sky Fraction



Figure . K-band performance for the Galaxy Assembly Science Case as a function of sky coverage percentage, representing the likely of finding three NGS of sufficient brightness to achieved the indicated performance, within the FoR of the LO WFS. The residual TT error varies from about 4 mas to about 9 mas as the sky coverage fraction is increased.

## Performance vs. LO WFS Passband



Figure . Residual TT error for the Galaxy Assembly Science Case as a function of sky coverage percentage, for three different choices of LO WFS passband. Inclusion of the design-complicating K-band is comparable to the uncertainty in our models, excepting perhaps at the highest sky fraction, where the advantage of including K-band would probably be real. Note, KAON 721 does not currently account for inter-filter-band sky emissions. Thus, these results should be considered for e.g. J + H, not the full range J through H. As such, the relative advantage of including K-band is probably overstated here.

## Performance vs. Spaxel Sampling



Figure . K-band Ensquared Energy vs. Spaxel Dimension for the Galaxy Assembly Science Case for NGAO correction and, for comparison, a seeing-limited PSF in median seeing conditions. (The relative transmission loss of NGAO compared to a Nasmyth-mounted seeing-limited instrument is not represented here – these curves reflect PSF shape only.)

# Appendix A: System Compliance Matrix

XXX This matrix is completed and posted to the TWiki. Should it or parts of it be included here? XXX

# Appendix B: Wavefront Error Budget Spreadsheet v2.0

XXX These are only snippets of text – will be cleaned up later XXX

KAON 721 consists of a Microsoft Excel spreadsheet encoding the following for the purposes of developing adaptive optics system error budgets and evaluating as-built adaptive optics system performance:

* AO system architectures and design choices
* Atmospheric turbulence models
* Telescope parameters and as-built optical performance metrics
* Astronomical detector properties, such as quantum efficiency, dark current, and read noise
* Numerous adaptive optics error budget terms, specific to any of several distinct AO system architectures (e.g. SCAO, MCAO, MOAO) for both NGS and LGS guide star modes
* Atmospheric dispersion
* Calibration and systematic error terms, such as thermally induced non-common-path flexure
* Several astronomical stellar density models for the evaluation of AO sky coverage

The spreadsheet also computes ensquared energy fractions using a core/halo model for the point spread function, and calculates sky coverage estimates for tip tilt guide stars employed in laser guide star architectures from common star density models.

XXX Include a paragraph on validation activities here XXX

The terms in the previously presented tables are largely self-explanatory, although their quantitative implementation requires reference to KAON 721 itself. All the same, a few items in Table 5 are worthy of additional explanation here:

* HO Flux, Number of Subapertures Across: NGAO has high-order wavefront sensors designed to sample the telescope pupil with ~60 subapertures across the 10.949 m maximum diameter. Our WFS’s, however, are designed for 63 x 63 subaperture format (e.g. oversizing the pupil somewhat) to handle known pupil nutation in the Keck telescopes. See Keck Drawing 1410-CM0010 for more detail.
* HO Flux, HO WFS CCD Read Time is currently given as a fraction of the HO WFS frame rate, which is typically an optimization variable. In the future, this will be replaced with an amplifier dwell time or equivalent parameter to specify the detector read time.
* LGS Flux, Na Column Density of 3e9 atoms/cm2 is below median density (approximately 25th percentile). See Figure XXX for a trade study of performance vs. sodium density.
* TT Flux, TT Compensation Mode is a complex choice that supports traditional single-conjugate AO correction, MCAO, single-LGS MOAO correction, and multiple patrolling LGS (aka ‘Point and Shoot’) architectures. Changes to this parameter must be carefully understood by the KAON 721 user.
* Atm Dispersion, Science Dispersion Corrector Factor uses a crude multiplicative (divisive, actually) factor to estimate the residual performance, if a science ADC is used. In the future, KAON 721 will allow for definition of more realistic, design-informed residual dispersion.
* Margins (e.g. performance margins) are held apart from physical error terms and constitute the difference between use of KAON 721 as an error budget (including margins) and as a performance prediction or system diagnostic tool (assuming margins are not invoked.)

# Appendix C: Detailed Error Budgets

XXX This is only a draft example of the screen captures for the ExoPlanets and Gal Center. These will be replaced in the final draft XXX

## Input Summary



## Galactic Center Case



ExoPlanet

1. A future revision to KAON 721 may support definable, selectable WFS frame rates, but this is not currently supported. [↑](#footnote-ref-1)
2. Slight revisions to the Key Science Cases have been made during PD phase. See McGrath and Max, “Science Case Parameters for Performance Budgets” for more details. [↑](#footnote-ref-2)
3. June 20, 2006 NGAO Design and Development Proposal, Table 13. [↑](#footnote-ref-3)
4. KAON 461, Table 1 for LGS mode with 18th magnitude TT star. [↑](#footnote-ref-4)
5. KAON 461, Appendix 3 for LGS mode with 18th magnitude TT star. [↑](#footnote-ref-5)
6. June 20, 2006 NGAO Design and Development Proposal, Figure 49, for 30% sky coverage, z = 30 deg, having 173 nm HO error and [↑](#footnote-ref-6)
7. Performance increase driven by reduced FoR for this science case brought on by Build-to-Cost decision to eliminate a d-IFU instrument from the NGAO program. [↑](#footnote-ref-7)
8. Jessica Lu, private communication, who reports NGWFC median performance of 401 nm RMS. Here, we assume Keck 1 LGS will provide the same improvement as shown in KAON 461, Table 2, for LGS with 10th magnitude TT star, namely the subtraction of 105 nm in quadrature, so sqrt(401^2 – 105^2) = 387 nm. [↑](#footnote-ref-8)
9. KAON 461, Table 1 for LGS mode with 10th magnitude TT star. [↑](#footnote-ref-9)
10. KAON 461, Appendix 2 for LGS mode with 10th magnitude TT star. [↑](#footnote-ref-10)
11. Performance decrease driven primarily by simplification to laser asterism and reduction in laser power. [↑](#footnote-ref-11)
12. KAON 461, Table 1 for NGS ‘bright star’ performance. [↑](#footnote-ref-12)
13. KAON 461, Appendix 1 for NGS mode with 8th magnitude TT star. Note, NGWFC should have similar performance, as the Keck 1 LGS upgrade will not affect NGS science performance. [↑](#footnote-ref-13)
14. We assume 75 ph/sec/cm2/W return from a 3 x 109 atoms/cm2 sodium layer (itself from Denman’s reported 150 ph/sec/cm2 from Albuquerque with 4 x 109 atoms/cm2 – see KAON 721), with 50W/4\*.6 (BTO)\*.88 (Atm) = 6.6 W per beacon delivered to mesosphere (495 ph/sec/cm2 at mesosphere), followed by T=0.35, QE=0.85 on the downlink results in about 155 ph/sec/cm2 detected by the WFS. [↑](#footnote-ref-14)
15. For these Gaussian distributions, we also truncate the distribution to avoid negative values. Although not strictly valid, in practice it has little effect on the results shown here (e.g. we’re not primarily interested in these rare outlier events.) [↑](#footnote-ref-15)